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IEEE Recommended Practice for the Application of Instrument Transformers in Industrial and Commercial Power Systems

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IEEE Recommended Practice for the Application of Instrument Transformers in Industrial and Commercial Power Systems

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Abstract: The selection and application of instrument transformers used in industrial and commercial power systems are covered in this recommended practice.
Keywords: CT, current transformer, IEEE 3004.1™, instrument transformer, voltage transformer, VT

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Introduction

This introduction is not part of IEEE Std 3004.1-2013, IEEE Recommended Practice for the Application of Instrument Transformers in Industrial and Commercial Power Systems.

IEEE 3000 Standards Collection™

This recommended practice was developed by the Technical Books Coordinating Committee of the Industrial and Commercial Power Systems Department of the Industry Applications Society as part of a project to repackage the popular IEEE Color Books®. The goal of this project is to speed up the revision process, eliminate duplicate material, and facilitate use of modern publishing and distribution technologies.

When this project is completed, the technical material in the thirteen IEEE Color Books will be included in a series of new standards—the most significant of which will be a new standard, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new standard will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional dot standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000™:

— Power Systems Design (3001 series)

— Power Systems Analysis (3002 series)

— Power Systems Grounding (3003 series)

— Protection and Coordination (3004 series)

— Emergency, Standby Power, and Energy Management Systems (3005 series)

— Power Systems Reliability (3006 series)

— Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a dot standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

The material in this recommended practice largely comes from IEEE Std 242™ (*IEEE Buff Book™*).

IEEE Std 3004.1™

This recommended practice covers the selection and application of instrument transformers used in industrial and commercial power systems.

Contents

IEEE Recommended Practice for the Application of Instrument Transformers in Industrial and Commercial Power Systems

1. Overview

1.1 Scope

This recommended practice covers the selection and application of instrument transformers used in industrial and commercial power systems.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std C57.13™, IEEE Standard Requirements for Instrument Transformers[1,2]

IEEE Std C57.13.3™, IEEE Guide for Grounding of Instrument Transformer Secondary Circuits and Cases

IEEE Std C57.13.6™, IEEE Standard for High-Accuracy Instrument Transformers

IEC Std 60044-1™, Instrument Transformers: Part 1—Current Transformers[3]

IEC Std 60044-2™, Instrument Transformers: Part 2—Inductive Voltage Transformers

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[4]

burden: The load connected to the secondary terminals, which may be expressed as voltamperes and power factor at a specified value of current, total ohms impedance and power factor, or ohms of the resistance and reactive components.

composite error: The root-mean-square (rms) of the instantaneous difference between the actual primary current and the actual secondary current multiplied by the rated current transformer transformation error.

current transformer (CT): Transforms line current into values suitable for use with standard protective relays and meters while isolating these instruments from line voltages.

dynamic current rating (I_{dyn}): The crest value of the asymmetrical primary current which a current transformer must withstand without being damaged electrically or mechanically by the resulting electromagnetic forces with the secondary winding short-circuited.

knee-point voltage: (A) The voltage at which a line tangent to the secondary excitation characteristic, when drawn on log-log coordinates, is at an angle of 45° to the horizontal. **(B)** The rated-frequency secondary voltage above which a 10% increase in voltage results in an increase of 50% or more in exciting current. (adapted from IEC)

polarity: The instantaneous phase relationship between the currents flowing in the primary and secondary of a current transformer. In simple applications, polarity is not important, but it is a critical consideration whenever multiple current transformers are used in combination, or when the output of a current transformer is used in conjunction with the output of a voltage transformer.

rating: The rating of a current transformer consists of a primary current rating and an associated secondary current rating. These ratings are related by the nominal transformation ratio of the current transformer, which is usually also the physical turns ratio of the transformer.

ratio correction factor (RCF): The ratio of the true, or measured, ratio of the current transformer to the marked, or nominal, ratio.

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[2] IEEE publications are available from The Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).
[3] IEC publications are available from the Sales Department of the International Electrotechnical Commission, 3 rue de Varembé, PO Box 131, CH-1211, Geneva 20, Switzerland (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org).
[4] *IEEE Standards Dictionary Online* subscription is available at: http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

ratio error: The degree to which the ratio correction factor deviates from the ideal, or textbook case, and is typically expressed in percent.

short-time thermal current rating: The maximum current that the current transformer can carry for a specified period of time.

transformer correction factor (TCF): Takes into account both the magnitude of error and any associated error in phase angle. TCF tends to be more of a concern in metering applications and is the factor by which the reading of a wattmeter may be adjusted to compensate for inaccuracies.

voltage transformer (VT): Transforms line voltage into values suitable for standard protective relays and meters while isolating these instruments from the stresses associated with the primary power system.

4. Current transformers

A current transformer (CT) transforms line current into values suitable for use with standard protective relays and meters while isolating these instruments from line voltages. A typical CT has two windings, designated as primary and secondary, which are insulated from each other. Most CTs are conventional in the sense that they are transformers consisting of winding on iron cores. However, air core CTs have been used in power system applications, and CTs utilizing optical technology are becoming available. The primary winding is connected in series with the circuit carrying the line current to be measured; and the secondary winding is connected to protective devices, instruments, meters, or control devices.

Ideally, CTs change the magnitude of the current being measured without changing the phase angle or wave shape of the current. Practically, however, the output of CTs does contain some error and distortion, and dealing with these errors and distortion is one of the primary challenges in applying CTs.

4.1 Equivalent circuit for current transformers

To understand the performance and application of CTs, it is necessary to start with an equivalent circuit. The circuit shown in Figure 1 is representative, although variations on this circuit may be found in various texts.

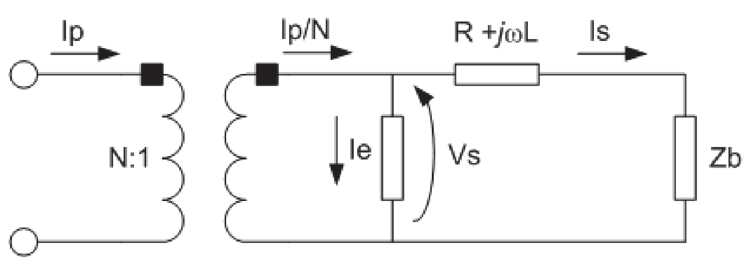

Figure 1—Equivalent circuit for a CT

In this equivalent circuit,

I_p	is the primary system current
I_s	is the secondary current fed to the meters or relays
N	is the nominal turns ratio of the CT
$R+j\omega L$	is the impedance of the CT secondary winding and leads, and the secondary wiring to the loads (meters or relays) applied to the CT

Z_b is the impedance of the load (meters or relays)

V_s is the voltage across the CT secondary

I_e is the exciting current drawn by the iron core of the CT

There are several important relationships depicted in this equivalent circuit. First, the secondary current produced by the CT is not equal to the primary current, divided by the CT turns ratio. Instead, there is an error due to the need to supply exciting current to the CT core. This relationship can be expressed algebraically as

$$I_s = \frac{I_p}{N} - I_e \tag{1}$$

Secondly, the secondary voltage, V_s, is a function of the secondary current and the total secondary burden impedance, including both external elements (the impedances of meters, relays, and interconnecting wiring) and the internal impedance of the CT secondary winding.

$$V_s = I_s \left[Z_b + R + j\omega L\right] \tag{2}$$

The third important relationship is that the exciting current, I_e, is a function of the CT secondary voltage, V_s. However, this is not a linear relationship, but rather is defined by a curve, called the CT secondary excitation characteristic, that represents the non-linear behavior of the iron core of the CT. Figure 2 depicts an idealized CT secondary excitation characteristic. Typically, the excitation characteristics are plotted on log-log paper. Therefore, even though some portions of the curve appear to be linear (i.e., a straight line), the relationship is actually non-linear.

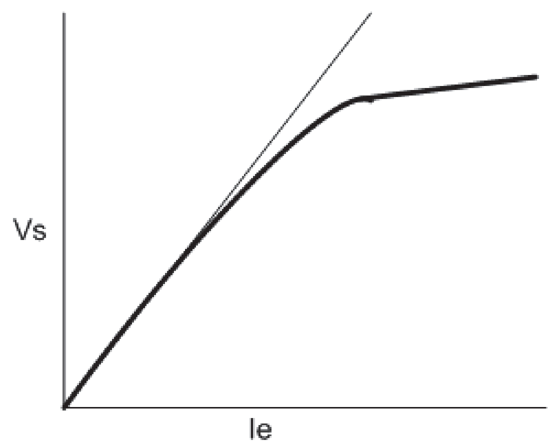

Figure 2—Idealized CT secondary excitation characteristic

The secondary excitation characteristic is derived from the hysteresis characteristic of the ferrous core of the CT. As V_s becomes large, there comes a point when the CT essentially becomes unable to sustain further increases in V_s. Referring to the equivalent circuit, further increases in I_p/N translate almost completely to increases in exciting current, I_e. At that point, the CT is said to be saturated.

Practical secondary excitation characteristics are usually published by CT manufacturers in the form of excitation current versus secondary rms voltage. The values are obtained either by calculation from transformer design and core-loss data or by testing a representative sample of the CTs produced by the manufacturer. The test is an open-circuit excitation current test on the secondary terminals, applying a variable sine wave voltage at rated frequency and recording rms current versus rms voltage.

A term that frequently appears in the technical literature is knee-point voltage. This is the voltage at the inflection point of the curve of V_s versus I_e (Figure 2). The working definition of knee-point voltage under

IEEE standards is that it is the voltage at which a line tangent to the secondary excitation characteristic, when drawn on log-log coordinates, is at an angle of 45° to the horizontal. Under IEC standards, knee-point voltage is defined as the rated-frequency secondary voltage above which a 10% increase in voltage results in an increase of 50% or more in exciting current.

Figure 3 is an example of a secondary excitation curve provided by a manufacturer for a specific CT design.

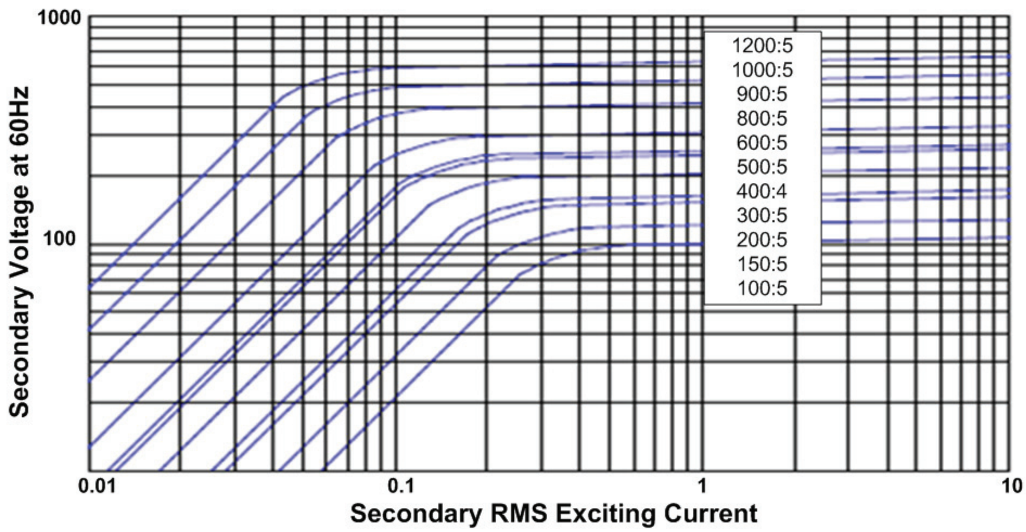

Figure 3—Typical CT secondary excitation curve

Detailed treatment of these issues is beyond the scope of this reference, but more comprehensive discussions can be found in other standards and in the technical literature. See [B1], [B2], [B3], [B4], [B6], [B10], [B11], and [B12].[5] In particular, IEEE Std C37.110™ [B7] includes an informative discussion of these topics.

4.2 Burden

Burden, in CT terminology, is the load connected to the secondary terminals. It may be expressed in several ways:

- Voltamperes and power factor at a specified value of current,
- Total ohms impedance and power factor, or
- Ohms of the resistance and reactive components.

The term burden is used to differentiate the CT load from the primary circuit load. The power factor referred to is that of the burden and not of the primary circuit.

[5] The numbers in brackets correspond to those of the bibliography in Annex A.

4.3 Current transformer ratings and performance parameters

4.3.1 Continuous current ratings

4.3.1.1 IEEE rating structure for current transformers

The terms "rating" and "ratio" tend to be used interchangeably in day to day practice, although "rating" is the more precise term.

The rating of a CT consists of a primary current rating and an associated secondary current rating. These ratings are related by the nominal transformation ratio of the CT, which is usually also the physical turns ratio of the transformer.

The preferred syntax for ratings is:
Primary current rating : secondary current rating

Under IEEE standards, most CTs have a 5-ampere secondary current rating. Table 1, extracted from IEEE Std C57.13™-2008, lists ANSI standard CT ratings for single ratio CTs. Table 2 lists standard ratings for multi-ratio CTs, while Table 3 lists standard ratings of CTs with dual ratios.

Table 1—IEEE standard current transformer ratings for single-ratio CTs

10:5	800:5
15:5	1200:5
25:5	1500:5
40:5	2000:5
50:5	3000:5
75:5	4000:5
100:5	5000:5
200:5	6000:5
300:5	8000:5
400:5	12 000:5
600:5	

Table 2—ANSI standard ratings for multi-ratio CTs

(Typically found in bushing CTs on power apparatus)

Current ratings (A)	Secondary taps		Current ratings (A)	Secondary taps	
600:5	50:5	X2-X3	3000:5	300:5	X3-X4
	100:5	X1-X2		500:5	X4-X5
	150:5	X1-X3		800:5	X3-X5
	200:5	X4-X5		1000:5	X1-X2
	250:5	X3-X4		1200:5	X2-X3
	300:5	X2-X4		1500:5	X2-X4
	400:5	X1-X4		2000:5	X2-X5
	450:5	X3-X5		2200:5	X1-X3
	500:5	X2-X5		2500:5	X1-X4
	600:5	X1-X5		3000:5	X1-X5
1200:5	100:5	X2-X3	4000:5	500:5	X1-X2
	200:5	X1-X2		1000:5	X3-X4
	300:5	X1-X3		1500:5	X2-X3
	400:5	X4-X5		2000:5	X1-X3
	500:5	X3-X4		2500:5	X2-X4
	600:5	X2-X4		3000:5	X1-X4
	800:5	X1-X4		3500:5	X2-X5
	900:5	X3-X5		4000:5	X1-X5
	1000:5	X2-X5			
	1200:5	X1-X5			
2000:5	300:5	X3-X4	5000:5	500:5	X2-X3
	400:5	X1-X2		1000:5	X4-X5
	500:5	X4-X5		1500:5	X1-X2
	800:5	X2-X3		2000:5	X3-X4
	1100:5	X2-X4		2500:5	X2-X4
	1200:5	X1-X3		3000:5	X3-X5
	1500:5	X1-X4		3500:5	X2-X5
	1600:5	X2-X5		4000:5	X1-X4
	2000:5	X1-X5		5000:5	X1-X5

Table 3—ANSI standard ratings for CTs with dual ratios

Double ratio with series-parallel primary windings (A)	Double ratio with taps in secondary winding (A)
25 × 50:5	25/50:5
50 × 100:5	50/100:5
100 × 200:5	100/200:5
200 × 400:5	200/400:5
400 × 800:5	300/600:5
600 × 1200:5	400/800:5
1000 × 2000:5	600/1200:5
2000 × 4000:5	1000/2000:5
	1500/3000:5
	2000/4000:5

Under IEEE standards, CTs are assigned a thermal rating factor. The actual thermal capacity of the CT windings is equal to:

$$Thermal\ capacity\ (amperes) = Current\ rating\ (amperes) \times Thermal\ rating\ \ factor$$

IEEE standards specify a variety of thermal rating factors, all for the case of a 30 °C ambient, as well as curves that may be used to adjust the thermal capacity for other ambient temperatures. The rating (ratio) of the CT as well as its thermal rating factor will usually be found on the CT nameplate as well as in manufacturer's literature.

Traditionally, those applications conceived and planned following IEEE standards employ CTs with 5A secondary ratings. European tradition favors CTs with 1A secondary ratings. As these traditions merge, the question of whether 1 A or 5 A ratings should be favored often arises. IEEE Std C37.110™ provides guidance on comparing the technical performance of these two different ratings in order to make an informed decision about which tradition to follow in a specific application.

The IEEE standards for CT continuous current ratings (such as IEEE Std C57.13™) describe the methodology for specifying those ratings. Other standards may impose constraints on the ratings that are available for specific applications. For example, some circuit breaker standards specify the minimum CT rating (ratio) that may be associated with circuit breakers as a function of the breaker voltage rating.

4.3.1.2 IEC rating structure for current transformers

IEC standards define the secondary current rating of CTs to be 1 A, 2 A, or 5 A, with 5 A being the preferred rating. However, there is a strong tradition in those parts of the world where IEC standards are applied to employ CTs with 1 A secondary current ratings.

IEC standards also define a set of standard and preferred primary current ratings. Standard ratings are 10 A, 12.5 A, 15 A, 20 A, 25 A, 30 A, 40 A, 50 A, 60 A, and 75 A and multiples thereof. Preferred ratings are 10 A, 15 A, 20 A, 30 A, 50 A, and 75 A and multiples thereof. IEC standards allow for multi-ratio CTs provided the lowest rating corresponds to one of the standard ratings.

Unless otherwise specified, the actual thermal capacity of an IEC-rated CT, designated as I_{th}, is the primary current rating of that CT. It is possible to specify a thermal capacity, I_{th}, in excess of the nominal primary current rating. When this is done, the preferred thermal capacities are 120%, 150%, or 200% of the nominal rating.

4.3.2 Short-time current ratings

There are two dimensions of short-time current ratings of CTs. These attributes of the short-time rating are not independent. The mechanical rating of CTs occasionally comes into play to determine the minimum CT rating (ratio) that may be used in an application in which the available short-circuit current is high.

The short-time thermal current rating is the maximum current that the CT can carry for a specified period of time. A common concern is to coordinate the short-time thermal capacity of CTs in relaying applications with the expected operating times of protective relays and circuit interrupting devices to minimize the risk of damage to the components protecting the system by the short-circuits they are intended to measure and act upon.

While short-time ratings of CTs are usually expressed in terms of primary system amperes, the actual limiting factor in window and bushing CTs is the thermal capacity of the secondary winding.

4.3.2.1 IEEE short-time rating for current transformers

Under IEEE standards, the mechanical withstand capability of a CT is the fully offset (asymmetrical) primary current that the CT can sustain, with its secondary shorted, without sustaining mechanical damage to the CT and while still meeting all other IEEE standard requirements.

IEEE standards define a 1 s short-term current rating. Standards also provide formulae for expressing the short-time withstand capability of a CT for times other than 1 s.

4.3.2.2 IEC short-time ratings of current transformers

IEC standards define a dynamic current rating, I_{dyn}, for CTs. I_{dyn} is the crest value of the asymmetrical primary current which a CT must withstand without being damaged electrically or mechanically by the resulting electromagnetic forces with the secondary winding short-circuited. The default value of I_{dyn} is 2.5 times the rated thermal current, I_{th}, and this value may be assumed to apply unless some other value appears on the CT nameplate.

4.4 Accuracy ratings

4.4.1 Metering CTs versus relaying CTs

Some CTs are rated for metering applications, while others are rated for relaying (protection) applications. There is no inherent design difference between relaying and metering CTs. Instead, the difference between these two types of CTs relates to the way their accuracy is specified.

In the case of relaying CTs, standards specify the accuracy of the CT at a magnitude of current that is (typically) at the high end of the practical range of available short-circuit currents over which the CT and its associated relays will be expected to perform correctly. By contrast, the accuracy of metering CTs is specified at a magnitude of current corresponding to practical loading in the primary circuit. While the accuracy specification may bias the selection of CT construction (e.g., metering applications often, but not always, utilize wound-type CTs), it is entirely possible that a single-ratio CT could be assigned accuracy specifications for both metering and relaying applications.

IEEE Std C57.13.6™ includes special provisions for CTs with higher accuracy.

4.4.1.1 IEEE accuracy ratings for current transformers

There are two important terms involved in IEEE accuracy specifications for current (or voltage) transformers. Ratio Correction Factor (RCF) is the ratio of the true, or measured, ratio of the CT to the marked, or nominal, ratio. A ratio correction factor of 1 implies perfect accuracy (i.e., a perfect CT), a situation that exists only in theory. Ratio error is the degree to which the RCF deviates from the ideal, or textbook case, and is typically expressed in percent.

Transformer Correction Factor (TCF) takes into account both the magnitude of error and any associated error in phase angle. TCF tends to be more of a concern in metering applications and is the factor by which the reading of a wattmeter may be adjusted to compensate for inaccuracies.

The process of defining standard accuracies for relaying and metering CTs requires a set of standard burdens as listed in Table 4.

Table 4—IEEE standard burdens for specifying accuracy classifications for 5 A CTs

Burdens	Standard impedance designation	Voltamperes	Power factor	For 5 ampere secondaries		
				R (Ω)	L (mhy)	Z(Ω)
Metering CTs	B-0.1	2.5	0.9	0.09	0.116	0.1
	B-0.2	5.0	0.9	0.18	0.232	0.2
	B-0.5	12.5	0.9	0.45	0.58	0.5
	B-0.9	22.5	0.9	0.81	1.040	0.9
	B-1.8	45.0	0.9	1.62	2.080	1.8
Relaying CTs	B-1	25.0	0.5	0.50	3.3	1.0
	B-2	50.0	0.5	1.9	4.6	2.0
	B-4	100.0	0.5	2.0	9.2	4.0
	B-8	200.0	0.5	4.0	18.4	8.0

4.4.1.2 IEEE accuracy rating for relaying current transformers

IEEE standards specify the relaying accuracy of CTs at a current magnitude equal to twenty times the rated current of the CT. Since the rating of most CTs designed under IEEE standards is 5 A (secondary), that means that the relaying accuracy is specified at a secondary current of 100 A.

Under IEEE standards, the accuracy of relaying CTs is described by specifying the secondary voltage the CT can develop at twenty times rated secondary current without exceeding 10% ratio error. No restriction is placed on phase angle error. On a typical CT, this amounts to specifying that the error is 10% or less at 100 A of secondary current, and the standard further requires that the error must not exceed 10% at secondary current levels below 100 A as well.

Standards define seven standard secondary voltage (accuracy) classes for CTs as listed in Table 5. Because these secondary voltages all apply at the standard 100 A secondary current level, there is therefore an associated secondary burden. These secondary burdens are used primarily in standardized type-testing of CTs.

Table 5—IEEE standard accuracy classifications for relaying CTs and associated standard burden impedances

Secondary voltage	Standard burden ohms at rated frequency
10	0.1
20	0.2
50	0.5
100	1.0
200	2.0
400	4.0
800	8.0

The standards also require that the accuracy specification include a further qualification that identifies whether the accuracy can be determined by means of analytical calculation, or if the accuracy can only be determined by following laboratory test procedures described in the standards. Referring to Figure 1, the fundamental technical consideration in this distinction is the magnitude of the $j\omega L$ term in the secondary impedance—if the secondary leakage inductance is very small (which would typically be the case if the secondary winding is fully distributed), then it is usually possible for the CT to carry a C, or calculated accuracy, rating. On the other hand, if the secondary leakage inductance is finite, then it may be necessary for the accuracy to carry a T, or test, rating.

IEEE standards also include a third, or special accuracy classification of relaying CTs. The so-called X classification defines accuracy for specific conditions by specifying the minimum knee-point voltage, the

corresponding maximum secondary excitation current, I_e, and the maximum allowable secondary resistance.

Therefore, typical examples of common accuracy specifications for relaying CTs under IEEE standards are:

C200 for a CT with a fully distributed secondary winding that can deliver 200 V across its secondary winding when the secondary current is 20 times the rated 5 A secondary current, or 100 secondary A, without exceeding 10% error in the secondary current

T200 for a CT with a non-distributed secondary winding that can deliver 200 V across its secondary winding when the secondary current is 20 times the rated 5 A secondary current, or 100 secondary A, without exceeding 10% error in the secondary current

IEEE standards on CT accuracy focus mainly on the methodology for specifying accuracy. Equipment standards within the IEEE structure may impose constraints on the accuracy ratings of CTs associated with equipment of specific ratings, and it may not be possible to obtain every possible accuracy class in every application. For example, standard CTs with lower ratings (ratios) tend to have lower accuracy classifications, and if application requirements demand higher accuracy in low-ratio applications, it may be necessary to specify CTs that exceed IEEE standard requirements. However, it is not always possible to physically accommodate higher accuracy CTs within standard electrical equipment because of space limitations.

The accuracy voltage rating of a CT applies to the full winding ratio, unless specified otherwise. On a multi-ratio CT, the voltage capability is reduced in direct proportion to the ratio between the tap value being used and the full winding.

4.4.1.3 IEEE accuracy rating for metering current transformers

IEEE standards specify the metering accuracy of CTs at the rated current of the CT.

IEEE standards provide three standard accuracy classes, differentiated by the factor required to correct the accuracy of the CT. The correction factor here is both the RCF and TCF. These classes are listed in Table 6.

Table 6—IEEE standard metering accuracy classes for CTs

Accuracy classification	Limits on correction factor	
	100% rated current	10% rated current
1.2	0.988-1.012	0.976-1.024
0.6	0.994-1.006	0.988-1.012
0.3	0.997-1.003	0.994-1.006

The metering accuracy of a CT is described by specifying the metering class together with the associated standard burden. For example, a very accurate CT might be described as:

0.3 B-0.1, 0.3 B-0.2, 0.3 B-0.5, 0.3 B-1, 0.3B-2, 0.3 B-4, 0.3 B-8

This specification implies that the CT meets accuracy class 0.3 for all standard burdens.

At the other end of the scale, a mediocre CT might be rated 1.2 B-0.1.

That the accuracy is specified only at the 0.1 burden means that the error on all other burdens exceeds the minimum classification (1.2) and no other rating can be given.

4.4.1.4 IEC accuracy ratings of current transformers

Under IEC standards, CTs are defined to have a rated output expressed in VA. Unless otherwise stated in the rating of the CT, the rated output is presumed to be 30 VA.

IEC standards define a current error factor for CTs as

$$Current\ error, \% = \frac{\left(K_n I_s - I_p\right) \times 100}{I_p} \tag{3}$$

Where

K_n is the rated CT transformation ratio

I_s is the actual secondary current

I_p is the actual primary current

IEC also defines a composite error which is the RMS of the instantaneous difference between the actual primary current and the actual secondary current multiplied by the rated CT transformation error.

4.4.1.5 IEC accuracy ratings of current transformers applied for relaying

IEC standards define the accuracy class of CTs applied for relaying to be numerically equal to the highest permissible percentage composite error at the rated accuracy limit primary current prescribed for the accuracy class concerned, followed by the letter "P" (for protection). Standard accuracy classes are 5P and 10P corresponding to 5% and 10% error, respectively. Table 7 defines the limits of error for protection CTs under IEC standards.

Table 7—Limits of error for CTs applied for protection under IEC standards

Accuracy classification	Current error at rated primary current, %	Phase displacement at rated primary current		Composite error at rated accuracy limit primary current, %
		Minutes	Centiradians	
5P	± 1	± 60	± 1.8	5
10P	± 3	—	—	10

4.4.1.6 IEC accuracy ratings of current transformers applied for metering

For metering CTs, IEC standards define an accuracy class designation that is numerically equal to the maximum permissible percentage current error at rated current prescribed for the accuracy class. Standard metering accuracy classes are 0.1, 0.2, 0.5, 1, 3, and 5 corresponding to 0.1%, 0.2%, 0.5%, 1%, 3%, and 5% error, respectively. Table 8 lists error limits for each of these accuracy classes.

Table 8—IEC accuracy limits for metering CTs

Accuracy class	± Percentage current (ratio) error at percentage of rated current shown below				± Phase displacement at percentage							
					Minutes				Centiradians			
	5%	20%	100%	120%	5%	20%	100%	120%	5%	20%	100%	120%
0.1	0.4	0.2	0.1	0.1	15	8	5	5	0.45	0.24	0.15	0.15
0.2	0.75	0.35	0.2	0.2	30	15	10	10	0.9	0.45	0.3	0.3
0.5	1.5	0.75	0.5	0.5	90	45	30	30	2.7	1.35	0.9	0.9
1	3	1.5	1.0	1.0	180	90	60	60	5.4	2.7	1.8	1.8
		50%		120%								
3	—	3	—	3	—	—	—	—	—	—	—	—
5	—	5	—	5	—	—	—	—	—	—	—	—

IEC standards include a special provision for metering CTs that may occasionally be encountered in industrial or commercial applications. For obvious reasons, CTs associated with revenue metering applications must have fairly high accuracy. The current available under fault conditions typically is many times that current that flows under normal conditions. This raises the concern about the consequences on sensitive metering devices of the high secondary currents that would be present in a metering circuit in the event of a fault.

IEC defines an instrument limit primary current (I_{PL}) at which the error due to saturation in the CT core is 10% or greater. Based on the definition of I_{PL}, the standard then defines an instrument security factor for metering CTs. The objective of these definitions it to provide a means to quantitatively describe the application in which a metering CT is intentionally designed to saturate severely at levels of current above rated load current but below the maximum fault current in order to minimize the thermal duty imposed on metering devices under fault conditions. The instrument security factor therefore can be used to coordinate the selection of a metering instrument with the selection of a CT. Note that this approach means that the CT and instrument are chosen as a coordinated system rather than as individual components.

4.5 Current transformer voltage and BIL ratings

4.5.1 IEEE voltage and BIL ratings for current transformers

The voltage rating of a current transformer should be coordinated with the voltage of the system in which it will be applied. It is common practice to apply window CTs rated 600 V to systems with higher voltages. This practice is done by passing fully insulated conductors through the window. The conductor insulation functions as the CT primary insulation providing a fully rated installation.

CTs also have a BIL rating that is coordinated with their associated nominal system voltage rating as listed in Table 9.

Table 9—IEEE BIL ratings for CTs

Nominal system voltage (kV)	Maximum line-to-ground voltage (kV)	BIL and full wave crest (kV)
0.6	0.38	10
2.4	1.53	45
5.0	3.06	60
8.7	5.29	75
15.0	8.9	110 or 95
25.0	16.0	150 or 125
34.5	22.0	200

4.5.2 Rated insulation ratings for current transformers under IEC standards

For CTs not having an actual primary winding (i.e., window type CTs), the insulation rating is 0.72 kV.

The insulation ratings of CTs with primary windings are as listed in Table 10. See Table 3 of IEC 60044-1 (2003) for higher voltages.

Table 10—IEC insulation ratings for CTs with primary windings

Maximum rms equipment voltage (U_m)	Rated power frequency withstand voltage (kV rms)	Rated lightning withstand voltage (kV crest)
0.72	3	—
1.2	6	—
3.6	10	20 40
7.2	20	40 60
12	28	60 75
17.5	38	75 95
24	50	95 125
36	70	145 170

NOTE—Where two lightning impulse ratings are shown, the higher rating is recommended for exposed applications.

4.6 Unusual service conditions

The design of CTs includes presumptions about various conditions of service including, but not limited to, ambient temperature, altitude, humidity, and potential environmental contamination. Both IEEE and IEC standards include special provisions for application of CTs in applications that fall outside the assumed normal conditions. Readers should consult the appropriate standards for guidance when applying CTs at high altitudes, in high temperature or humidity environments, in situations in which surface contamination from the environment is anticipated, or in other circumstances that fall outside standard service conditions as defined in those standards.

4.7 Current transformer construction

4.7.1 Wound-type current transformers

A wound-type CT has a physical primary winding consisting of one or more turns mechanically encircling the core or cores. The primary and secondary windings are insulated from each other and from the core(s) and are assembled as an integral structure.

In industrial applications, wound-type CTs are generally noted for higher accuracy than other forms of construction and are often available with dual secondaries. However, wound-type CTs do not always have fully distributed secondary windings, leading to a higher secondary leakage inductance. Because there is a physical primary winding, wound-type CTs have a defined primary voltage rating. Wound-type CTs also tend to be more expensive than other forms of CTs.

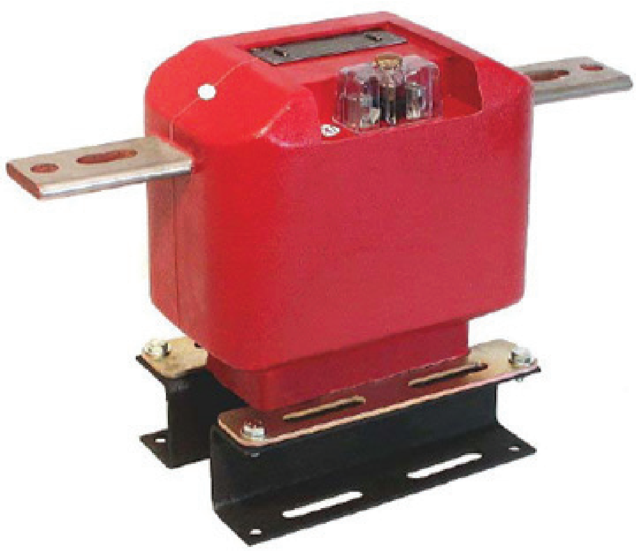

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Figure 4—Wound-type current transformer

4.7.2 Bar-type current transformers

A bar CT has a fixed, insulated, straight conductor in the form of a bar, rod, or tube that is a single primary turn passing through the magnetic circuit and is assembled to the secondary, core, and winding as depicted in Figure 5. In application, the primary bar is connected directly into the primary power system conductor such that all of the current in the primary current flows through the bar.

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Figure 5—Bar-type current transformer

Because there is a physical primary winding, bar-type CTs are intended for a specific primary voltage and are not available at all voltages.

4.7.3 Window-type current transformers

A window CT has a secondary winding insulated from and permanently assembled on the core, but it has no primary winding as an integral part of the structure. Instead, the primary conductor passes through the opening in the CT and becomes the primary winding (see Figure 6). The secondary windings of window-type CTs are usually fully distributed around the core.

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Figure 6—Window-type current transformer

Window-type CTs are available in single-ratio, multi-ratio, and dual secondary configurations.

In special applications, it is possible to pass the primary conductor through the CT window several times to increase the apparent sensitivity of the application. This should normally be done only in consultation with the CT manufacturer.

4.7.4 Bushing-type current transformers

A bushing CT is similar to a window-type CT, having an annular core and a secondary winding insulated from, and permanently assembled on, the core. This type of CT is used with a fully insulated conductor as the primary winding and typically used in equipment where the primary conductor is a component part of other apparatus, for example, on bushings of a transformer or circuit breaker.

The secondary windings of bushing CTs are usually fully distributed around the core. Typically they are multi-ratio with each winding tap also being fully distributed.

4.7.5 Split-core current transformers

Split-core CTs are similar to window-type CTs but are designed to be installed without requiring disconnection and reconnection of primary conductors. Split-core CTs have a secondary winding insulated from, and permanently assembled on, the core but have no primary winding as an integral part of the structure. One or more turns of the line conductor can be passed to provide the primary winding. Primary insulation is provided by the insulation of that primary conductor. The core, however, is split in a way that allows it to be slipped around the primary conductor, then reassembled to create a complete magnetic circuit. Split-core CTs rarely have fully distributed secondary windings and therefore have a significant inductive component in the secondary winding impedance. Therefore, the performance of these CTs can be determined only by test.

One of the most common examples of a split-core CT is the clamp-on ammeter.

4.7.6 Auxiliary current transformers

Auxiliary CTs are used in the secondary circuit of prime CTs, usually to modify the magnitude of secondary current, but occasionally to introduce a phase angle shift or to create a path to block the flow of zero sequence currents. Generally, auxiliary CTs have wound-type and secondary windings, but occasionally a window-type device may be used as an auxiliary CT.

4.7.7 Air-core current transformers (linear couplers)

4.7.7.1 Linear couplers

Air-core CTs are sometimes referred to as linear couplers. Because these devices do not have an iron core with an inherent hysteresis characteristic, they do not display the saturation characteristic typical of iron core CTs.

On the other hand, the transformation characteristic of air-core CTs cannot be expressed in terms of a current ratio. Instead, the output of an air-core CT is a voltage that is related to the input current.

Air-core CTs have been used in specialized protection applications in which the protective relay was designed to operate on voltage rather than current. The most notable example was a form of bus differential protection. Linear coupler bus differential protection was a practical option in air-insulated outdoor substations but was cost-prohibitive in indoor metal-clad applications at medium voltage.

4.7.7.2 Flexible-core CTs

Another type of air-core CT, which is often made so it can be installed on equipment that is energized, is a flexible-core CT. The flexible-core CT is an air-core transformer (also known as a Rogowski coil, named after the man who developed it). The flexible-core CT has a spiral winding wound around a non-magnetic material. The flexible-core CT requires an operational amplifier since the output is a voltage proportional to the rate of change of the current. Because the coil does not use magnetic material, it has low inductance and does not saturate. Therefore, it can measure high current levels and high frequency changes much more accurately than a conventional CT. This makes it ideal for power quality metering since the waveshape of switching transients can be much more accurately captured with a Rogowski coil than with a conventional CT.

Flexible-core CTs have become the norm for use with portable power meters and power quality meters. They are also becoming more common in permanent installations due to their ease of installation and electrical characteristics.

4.7.8 Optical current transformers

Optical CTs use sensors applied in close proximity to the primary bus and coupled to the protection relays and meters using digital fiber optic circuits. While not widely used, optical CTs are becoming commercially available for some applications.

4.8 Current transformer connections

4.8.1 CT polarity

Polarity refers to the instantaneous phase relationship between the currents flowing in the primary and secondary of a CT. In simple applications, polarity is not important, but it is a critical consideration whenever multiple CTs are used in combination, or when the output of a CT is used in conjunction with the output of a VT. Examples of applications where this can be a concern include metering (of both real and reactive power) and directional relaying.

Marks on both drawings and physical CTs designate the relative instantaneous directions of currents. At the same instant that the primary current is entering the marked primary terminal, the corresponding secondary current is leaving the similarly marked secondary terminal, having undergone a magnitude change within the transformer.

On drawings, polarity is noted either by placing a mark near one end of the winding or by terminal designations. For example, a primary terminal designated H1 is considered polarity with respect to a secondary terminal designated X1.

On the physical CT, the primary H1 and secondary X1 terminals are marked with painted dots, a raised symbol molded into the CT, or by designations on terminal blocks such as H1 and X1.

4.8.2 Three-phase wye connection

In the wye connection, a CT is placed in each phase. The secondary current from these CTs is therefore a replica of the primary current both in magnitude and phase angle. The normal practice is to apply relays (and meters, where required) in each of the three secondary circuits. In this configuration, balanced three-phase conditions on the primary will be faithfully seen by the devices in all three of the secondary circuits,

while phase-to-phase fault or load conditions will be seen by the relays or meters in the respective secondaries.

For conditions involving currents flowing in one phase of the primary and circulating back through ground, replica currents will flow only in the one corresponding secondary circuit. In that instance, it is common to apply a relay in the common return of the three secondary circuits, also called the residual and typically designated with the suffix N. A relay in the neutral return path, shown in Figure 7 as N, will measure unbalanced phase currents, or currents flowing to ground.

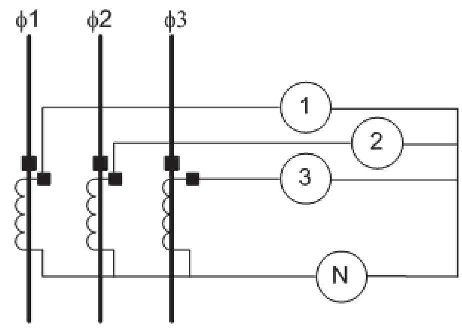

Figure 7—Wye-connected CTs

4.8.3 Three-phase open-wye connection

Sometimes referred to as a vee connection, the open-wye connection is a wye with one leg omitted, using only two CTs. Applied as shown in Figure 8, this connection detects three-phase and phase-to-phase faults or load conditions. Other means are required to detect ground-fault currents. Commonly used in the distant past in industrial applications for economy, the open-wye connection is no longer recommended.

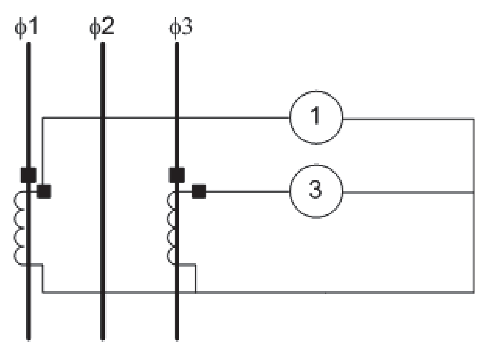

Figure 8—Open wye-connected CTs

4.8.4 Three-phase delta connection

A delta connection uses three CTs with the secondaries connected in delta before the connections are made to secondary meters or relays (see Figure 9). There are four characteristics of the delta connection that influence its application:

— For balanced three-phase fault or load conditions, the currents on the secondary are displaced from the corresponding currents on the primary by 30°. Whether that phase shift is forward or backward depends on how the delta connection is made up.

— Zero-sequence components of primary current will be trapped within the delta-connected CT secondary and will not flow out to be measured by the secondary relays or meters. As a result, the secondary devices will be unable to respond to zero-sequence current in the primary.

— The currents on the secondary for a balanced three-phase fault or load condition are equal to the primary current, divided by the nominal CT rating (ratio), multiplied by √3.

— For a phase-to-phase fault, two of the secondary meters or relays will see a magnitude of current equal to the actual primary current divided by the nominal CT rating (ratio), while the third secondary device will see a magnitude of current that is 1.16 times larger than the other two.

The delta connection has traditionally been used in conjunction with traditional, discrete-function relays in applications where the first two of these characteristics are important. For example, an angular shift may be important in applying differential protection on transformers, while the ability to block zero sequence is helpful in providing protection to shunt reactors and neutral deriving transformers. However, the ability of modern digital relays to calculate currents using fundamental equations may make the delta connection less common in the future.

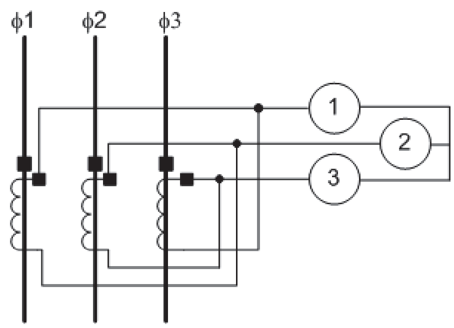

Figure 9—Delta-connected CTs

4.8.5 Balanced-flux connection

The balanced-flux, or zero-sequence CT is a single large-diameter CT that encircles all three phases of the primary circuit. See Figure 10. The net flux in this situation is associated with only the zero-sequence component of current in the primary system. The relays or meters served by this CT connection respond only to zero sequence quantities.

This connection is widely used as a means of providing sensitive ground-fault protection on feeders in low-resistance grounded medium-voltage industrial systems. It should not be applied where the system neutral is effectively grounded because the high available magnitudes of ground-fault current will be too high for it to be effective.

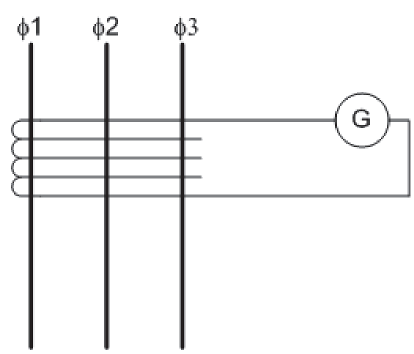

Figure 10—Zero-sequence CT

There is an important installation consideration with this CT connection. In many medium voltage applications (actually, most applications at 4.16 kV and above), feeder cables are equipped with a metallic sheath that is grounded at both ends to equalize voltage stress along the cable. In the event of a ground-fault anywhere in the medium voltage system, ground-fault current can circulate back through the sheath on unfaulted feeders.

To prevent incorrect operation of relays connected to a zero-sequence CT, it is essential that the sheath not extend electrically through the CT. Practically, this means that the connection from the sheath to the ground be made on the load-side of the CT—the pigtail from the sheath should be fed back through the CT prior to being grounded as depicted in Figure 11.

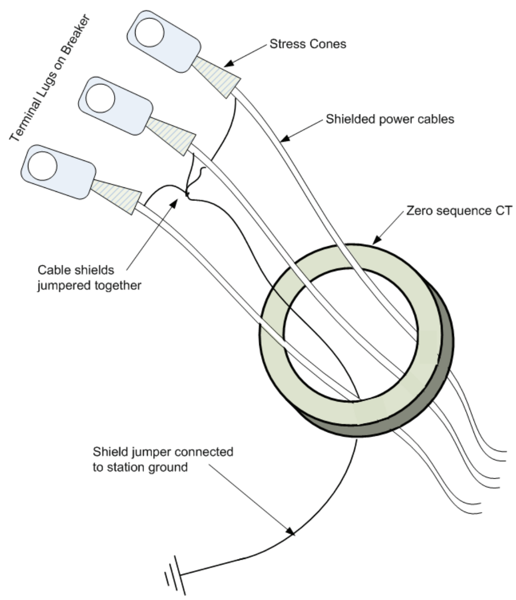

Figure 11 —Physical installation of a zero-sequence CT showing proper termination of medium voltage cable shields

4.8.6 Zero sequence shunt

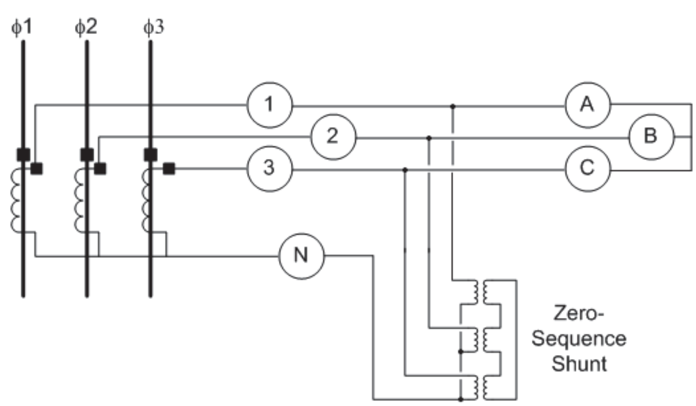

Figure 12 —Zero-sequence shunt

The zero-sequence shunt is a special connection of auxiliary CTs used primarily in protection applications. Wye-connected CTs (see Figure 7) produce secondary currents that reflect the zero-sequence content of

primary current. There are instances, for example in providing overcurrent protection of neutral-deriving transformers, when it is helpful for at least some relays to be insensitive to zero-sequence current.

Figure 12 shows three auxiliary CTs configured as a zero-sequence shunt. Typically, auxiliary CTs used in this application have a 1:1 ratio. Zero-sequence current circulates between the wye connection of the primary CTs and the wye connection of the shunt, and the relays in this region (relays 1, 2, 3, and N) therefore will see currents containing a zero-sequence component. Zero-sequence currents cannot circulate to the right of the shunt in Figure 12, so relays A, B, and C do not see a zero-sequence component.

4.9 Current transformer application guide

4.9.1 Selection of CT current ratings (ratio)

Since CTs exist primarily to support metering and relaying applications, the criteria for properly selecting the rating (ratio) of a set of CTs depend greatly on the function that the meters and relays are intended to achieve, and CT selection really becomes a subset of the application of meters and relays.

That said, there are a few very general criteria that may be helpful in selecting CT ratings.

— The limiting thermal capacity of a CT is related to its rating, and it would be generally unwise to select a CT rating that would expose the CT to potential thermal hazard under normal, expected load conditions. That is, the actual thermal capacity of a set of CTs should always be greater than the maximum anticipated continuous load in the primary power circuit in which the CTs will be applied.

— Meters are often included in CT circuits, mainly for the convenience of system operators. When meters are present, operators have a realistic expectation that those meters will be useful under both normal, light load conditions, and abnormal heavy load conditions. Also, the load that a system is expected to carry will often increase beyond the expectation that is identified at the time the system is first constructed. Under both the IEEE and IEC systems of standards, the ratings of CTs are coordinated with the ratings of meters and relays. That is, if the CT rating is 5 A (under IEEE standards), then the corresponding standards for meters and relays also call for a nominal continuous current rating of 5 A. A similar statement can be made about 1 A equipment under IEC standards. In the case of analog meters, the current rating usually is that magnitude of current that will result in full-scale deflection of the meter. Therefore, a criterion that is often helpful is to select a CT rating at about 150% of the maximum load current in the circuit to be measured at the time of initial construction. With that selection, the initial full load current will result in about 2/3 of full scale meter deflection. That will leave margin on the low current side to be able to measure light load conditions with reasonable accuracy, as well as to meter overload or future load growth scenarios.

— Selecting the CT in a circuit that does not experience a normal continuous current is more of a challenge. A good example of this is selecting the CT for the neutral of a generator or transformer where there is no normal continuous current, and current will flow only under abnormal, ground fault conditions. In these situations, it is usually necessary to start the application with an assumption about the sensitivity of the relay that will operate on the CT secondary current, combined with a system-level application objective about the level of sensitivity that is desired for ground-fault detection.

4.9.2 Comments on burden and saturation

CT burden and saturation are important application considerations, especially in protection applications. There is no way to avoid saturation, so there will always be some error in the effective ratio of a CT applied

to meters or relays. The objective has to be to specify equipment that will result in an acceptable compromise between error and the cost of avoiding error.

Accuracy standards mainly provide terminology for use when writing specifications that describe the equipment being purchased for an application. In order to examine the performance of a set of CTs, relays, and meters, it may be necessary to go back to the fundamentals of CT performance, and that requires working with the equivalent circuit in Figure 1.

That in turn means that much more data will be required, including at least the following:

- The actual secondary excitation characteristic for the CT to be used (similar to Figure 3) as supplied by the CT manufacturer
- The secondary winding resistance of the CT from the CT manufacturer
- The secondary leakage inductance of the CT from the CT manufacturer
- The length and resistance of the CT secondary leads. The inductance of the secondary leads is usually small and can be neglected.
- The impedance burden of every secondary device in the CT circuit—relays, meters, transducers, etc.

In most instances, it is possible to assess the accuracy of an application using fairly simple analysis of the equivalent circuit. If the secondary leakage inductance of the CT is negligible, the analysis can be conducted using scalar arithmetic. And even in cases where that inductance is finite, it is often possible to approximate a solution by treating the inductance as an increment component of resistance.

There are generally two problems that may have to be addressed in analyzing burden and saturation:

a) What is the primary (system level) current sensitivity of a relay with a known pickup setting?

b) What is the magnitude of current that will be presented to a relay given a known magnitude of primary (system level) current?

The process for addressing the first question is relatively simple and consists of four steps.

1. Draw the equivalent circuit (similar to Figure 1), and insert all impedance values.
2. Using Equation (2), calculate the total secondary voltage drop across the CT secondary (V_s in Figure 1) at the magnitude of fault current (I_s in Figure 1) at which the relay is expected to operate, taking into account the CT secondary winding resistance, secondary leakage inductance (if significant), secondary lead resistance, and impedance burden of all secondary components. If the CT is tapped, it is important to use the CT secondary winding resistance at the actual tap used in the application. If the evaluation is being made for a hypothetical three-phase fault, the lead resistance is the resistance of the wiring between the CT secondary and the neutral point of the CT secondary circuit. If the evaluation is being made for a hypothetical single-line-to-ground fault, the lead resistance is the round trip secondary resistance, or twice the resistance between the CT secondary and the neutral of the CT secondary circuit.
3. Knowing the CT secondary voltage (V_s in Figure 1), determine the corresponding CT exciting current (I_e in Figure 1) from the CT secondary excitation curve. In the case of a ground-fault application with wye-connected CTs, the CTs on the unfaulted phases are also excited, so the active (faulted phase) CT will be required to supply three times the exciting current read from the excitation curve.
4. Knowing the nominal turns ratio, relay current I_s, and I_e, calculate the primary current required to produce the total secondary current (relay current plus exciting current) using Equation (1).

The alternate problem presents greater analytical challenges.

a) Draw the equivalent circuit (similar to Figure 1) and insert all impedance values.

b) Knowing the primary (system level) maximum fault current (I_p) and the nominal CT turns ratio, calculate the idealized secondary current (I_p/N in Figure 1).

c) Assume a value of I_e.

d) Using Equation (1), calculate the secondary current, I_s.

e) Knowing the secondary current, I_s, calculate the secondary voltage drop across the CT secondary, V_s.

f) From the calculated CT secondary voltage, V_s, determine a refined value of I_e from the secondary excitation curve.

g) Repeat steps d) through f) until the value of secondary current no longer changes (significantly) between iterations.

The steps outlined here describe the process in which the only non-linearity in the circuit is the relationship between the magnitude of secondary voltage and the magnitude of exciting current, and currents and voltages are assumed to be rms sinusoidal quantities. More elaborate calculating procedures are described in IEEE standards [B7] and in the technical literature [B8]. In extreme cases, is may be necessary to model the CT circuit using a tool such as the Electromagnetic Transients Program (EMTP).

Ultimately, however, the issue is that of managing CT saturation to achieve satisfactory performance. Among the techniques that should be considered are:

— Specifying higher accuracy CTs. While this is an obvious step, it is important to recognize that merely specifying higher CT accuracy does not necessarily achieve a desired level of overall accuracy. Furthermore, calling for higher accuracy will almost certainly increase cost. And specifying unrealistically high accuracy requirements may limit the number of potential vendors, further complicating the economics of a project.

— Increasing the CT rating. Since higher accuracy tends to follow higher CT ratings, calling for higher ratings may help improve accuracy. Obviously, the challenge here will always be the anomalously small feeder on a stiff bus where the expected full load current would normally drive the CT rating lower.

— Reducing the burden of secondary devices. This was a major difficulty with older discrete relays and meters, but is much easier to accomplish with digital technology.

— Avoid the use of auxiliary CTs to increase the sensitivity of protective devices. Auxiliary CTs increase the burden of devices reflected onto the main CTs, and the reduction in accuracy may more than offset the apparent increase in sensitivity.

— Reducing the resistance of the secondary leads. Designing the physical arrangement to have the relays and meters closer to the CTs is not always practical, but it is possible to reduce CT resistance by specifying CT wire with a larger cross-sectional dimension.

— In extreme instances, it is possible to achieve higher accuracy by using multiple CTs in series.

— Revisit the selection of CT continuous current ratings—1 A versus 5 A.

4.9.3 CT safety

4.9.3.1 Open-circuit operation of CTs

CTs should never be operated with the secondary circuit open-circuited. Referring to Figure 1, when the secondary is open, the entire secondary current is forced to flow through the equivalent exciting circuit of the core. Referring to Figure 2, when the exciting current increases, the open circuit secondary voltage also increases. Therefore, operating a CT with the secondary open circuit will result in the creation of potentially hazardous secondary voltages. Any CT that is known to have been subjected to open secondary circuit operation should be examined for possible damage before being returned to service.

Unused CTs should be shorted and grounded.

Many manufacturers use special shorting-type terminal blocks in CT circuits. It is also a common practice to provide test switches or blocks in CT circuits in equipment to allow connection of test equipment without having to disconnect CT wiring.

4.9.3.2 CT secondary switching

Related to the issue of open-circuited operation is the issue of switching CT secondaries. Normally, CT secondary switching should be avoided out of concern for either brief moments of open-circuit operation, or for failure of the switching scheme that would leave the CT open-circuited. However, there have been successful applications involving automatic switching in CT circuits in which the risks have been moderated by the application of voltage suppression devices to limit the maximum open-circuit secondary voltage.

4.9.3.3 Special consideration for tapped CTs

CTs with tapped secondary windings present additional considerations. When the tap selected for an application represents only a portion of the secondary winding, the secondary voltage, V_s, appears across the tapped portion of the winding. But the total winding acts as an autotransformer, producing an open-circuit voltage across the full winding that is equal to the secondary voltage multiplied by the ratio of the turns in the full winding to the turns in the tapped portion of the winding. Care should be taken that the voltage across the full winding does not exceed the voltage rating of the winding.

When taps are utilized on multi-ratio CTs, unused taps should not be shorted or grounded. Burden should be connected to the two active terminals of the multi-ratio CTs as needed with other terminals left open.

4.9.3.4 CT circuit grounding

The mini-system consisting of the CT secondary circuit and its associated components is like any other power system; to minimize transient voltage excursions, it is important that the neutral of that system be grounded.

It is customary to ground the neutral of wye-connected and vee-connected CTs. Delta-connected CTs are normally corner-of-the-delta grounded for safety. One terminal of zero-sequence CTs should also be grounded for safety.

There is, however, room for debate about the ideal location for applying that one ground. Traditionally, the neutral of a power system is grounded at the source. In the case of CT circuits, the source is at the CTs themselves. The problem is that the CTs are often in a remote, inconvenient location. From a service point

of view, it might be more convenient to ground the CT circuit at the point where it enters the control cabinet.

Unlike other power systems applications, there may be a problem with applying multiple grounds in CT circuits. If there are two or more grounds at locations that are physically separate, a potential gradient between those two locations could introduce a spurious voltage into a CT circuit that could drive a secondary current that could lead to erroneous relay operation.

4.9.3.5 CTs on capacitor circuits

When power factor capacitors are switched, it is normal for there to be a high-frequency current transient on the power system. These high-frequency transients can generate high-frequency voltage spikes in the secondary of CT circuits. Use of transient voltage suppression devices (i.e., non-linear resistors, MOV devices, etc.) may be appropriate to manage these situations.

4.9.3.6 CT applications with abnormal frequency

CTs are designed to be applied on power systems where the operating frequency matches the frequency rating specified by the manufacturer. CT experience increased saturation at reduced frequencies, and other anomalous performance characteristics at frequencies significantly greater than rated. Applications involving measurements at frequencies other than rated should be reviewed with the respective CT manufacturer.

5. Voltage (potential) transformers

5.1 Functional definition

A voltage transformer (VT) transforms line voltage into values suitable for standard protective relays and meters while isolating these instruments from the stresses associated with the primary power system. A simple VT has two windings, designated as primary and secondary, which are insulated from each other. VTs are available with multiple primary and secondary windings. Most VTs are conventional in the sense that they are transformers consisting of windings on iron cores. However, capacitive voltage transformers (CVTs, sometimes called capacitively coupled voltage transformers, or CCVTs) are used in power system applications. Older literature routinely used the term potential transformer (PT), in place of voltage transformer (VT).

Ideally, VTs change the magnitude of the voltage being measured without changing the phase angle or wave shape of the voltage. Practically, however, the output of VTs may contain some distortion. Magnitude or angular distortion in the output of VTs is usually not a major problem.

5.2 Voltage transformer performance

5.2.1 Saturation

Unlike CTs, where the effects of saturation of the magnetic core material leads to concerns about measurement accuracy, most VTs are exposed only to core saturation problems when the applied system voltage is abnormally high. The vast majority of measurements that a VT will be expected to make are

under either normal system voltage conditions (i.e., normal loading) or fault conditions that will coincidentally result in depression of system voltage.

That said, it is important to be aware that applying excessive burden on VTs can result in errors in the voltage seen by meters and relays due to voltage drop in the secondary resistance of the VT winding or the secondary leads.

However, there is a concern related to the magnetic characteristics of VT core steel that application engineers do need to be concerned about. Specifically, if a VT is very lightly loaded, a situation can arise in which a resonance can exist between the inductive magnetizing reactance of the VT and system capacitance. This phenomenon, called ferroresonance, can result in elevated secondary voltages that can damage the VT as well as measuring devices connected to its output [B13]. Instances have been reported in which the inherent parasitic capacitance in the bushings of high-voltage VTs is sufficient to trigger ferroresonance. The problem has been addressed in a number of technical papers [B13]. Solutions usually involve application of appropriate grounding practices as well as assuring that the VT is never operated at no-load.

5.3 Voltage transformer ratings and performance parameters

5.3.1 IEEE voltage transformer rating structure

IEEE standards identify five rating parameters for voltage transformers:

a) Basic impulse insulation level in terms of full-wave test voltage
b) Rated primary voltage and ratio
c) Rated frequency
d) Accuracy ratings
e) Thermal burden rating

5.3.1.1 IEEE voltage ratings

Under IEEE standards, VTs have a rated primary voltage and a marked ratio. This combination often results in an open circuit secondary voltage of 120 V. It is relatively common for VT secondaries to be tapped to allow flexibility in how the secondary is connected.

Table 11—IEEE ratings and characteristics of VTs with 100% of rated primary voltage across the primary winding when connected line-to-line or line-to-ground

Rated VT primary voltage/rated system voltage line-to-line (V)	Marked ratio	Basic impulse insulation level (kV crest)
120 / 208 Y	1:1	10
240 / 416 Y	2:1	10
300 / 520 Y	2.5:1	10
120 / 208 Y	1:1	30
240 / 416 Y	2:1	30
300 / 520 Y	2.5:1	30
480 / 832 Y	4:1	30
600 / 1040 Y	5:1	30
2400 / 4160 Y	20:1	60
4200 / 7280 Y	35:1	75
4800 / 8320 Y	40:1	75
7200 / 12 470 Y	60:1	110 or 95
8400 / 14 560 Y	70:1	110 or 95

Table 12—IEEE ratings and characteristics of VTs primarily for line-to-line service

Rated VT primary voltage for rated system voltage line-to-line (V)	Marked ratio	Basic impulse insulation level (kV crest)
120 / 120 Y	1:1	10
240 / 240 Y	2:1	10
300 / 300 Y	2.5:1	10
480 / 480 Y	4:1	10
600 / 600 Y	5:1	10
2400 / 2400 Y	20:1	45
4800 / 4800 Y	40:1	60
7200 / 7200 Y	60:1	75
12 000 / 12 000 Y	100:1	110 or 95
14 000 / 14 000 Y	120:1	110 or 95
24 000 / 24 000 Y	200:1	150 or 125
34 500 / 34 500 Y	300:1	200 or 150

NOTE—May be applied line-to-ground or line-to-neutral at a winding voltage equal to the primary voltage rating divided by √3.

5.3.1.2 IEEE accuracy rating for voltage transformers

Standard accuracy classifications of VTs range from 0.3 to 1.2, representing percent ratio corrections to obtain a true ratio. These accuracies are high enough so that any standard transformer is adequate for most industrial protective relaying purposes as long as it is applied within its open-air thermal and voltage limits. Standard burdens for VTs with secondary voltages between 115 V and 120 V are shown in Table 13.

Table 13—Standard burdens for VTs

Characteristics on standard burdens			Characteristics on 120 V basis and rated frequency		
Designation	Voltamperes	Power factor	Resistance (Ω)	Inductance (mH)	Impedance (Ω)
W	12.5	0.10	115.2	3.04	1152
X	25	0.70	403.2	1.09	576
Y	75	0.85	163.2	0.268	192
Z	200	0.85	61.2	0.101	72
ZZ	400	0.85	30.6	0.0503	36
M	35	0.20	82.3	1.07	411
NOTE—These burden designations have no significance except at 60 Hz.					

As noted earlier, the thermal burden on a VT is typically more of a concern than is saturation. Thermal burden limits, as given by transformer manufacturers, should not be exceeded in normal practice because transformer accuracy and life will be adversely affected. Thermal burdens are given in voltamperes and may be calculated by simple arithmetic addition of the volt-ampere burdens of the devices connected to the transformer secondary. If the sum is within the rated thermal burden, the transformer should perform satisfactorily over the range of voltages from 0% to 110% of the nameplate voltage.

5.3.2 IEC rating structure for voltage transformers

Under the IEC structure, voltage transformers have the following ratings:

a) Rated primary voltage and rated secondary voltage

b) Rated output power

c) Rated voltage factor. The voltage factor defines maximum continuous overvoltage withstand capability for conditions in which the actual primary voltage exceeds the rated primary voltage as a consequence of variations in system grounding.

d) Rated temperature rise

5.3.2.1 IEC voltage ratings for voltage transformers

IEC defines the rated secondary voltage of VTs according to the prevailing practices in the geographic region where the VT is applied. Specifically, standard secondary voltages for single-phase VTs, VTs connected line-to-line in three-phase systems, or three-phase VTs are:

In European countries:	100 V or 110 V
	200 V for extended secondary circuits
In North America:	120 V for distribution systems
	115 V for transmission systems
	230 V for extended secondary circuits

IEC standards also provide for rated secondary voltages equal to one of the values given above divided by √3.

The rated continuous output (in VA) of VTs under IEC standards is a value selected from the following list:

10 VA, 15 VA, 25 VA, 30 VA, 50 VA, 75 VA, 100 VA, 150 VA, 200 VA, 300 VA, 400 VA, and 500 VA.

Of these, the preferred ratings are 10 VA, 25 VA, 50 VA, 100 VA, 200 VA, and 500 VA.

The rated primary voltage of a VT is any of the rated system voltages defined in IEC 60038. Standards also allow for VT ratings equal to 1/√3 times any of the rated system voltages for single-phase VTs.

IEC standards also specify a voltage factor that is dependent on the means of grounding the neutral of the system and the primary winding of the VT. This voltage factor is intended to be used as a multiplier on the rated primary voltage to determine the maximum allowable applied voltage as a function of both time and the means of grounding. Table 14 defines these voltage factors.

Table 14—Standard values of VT voltage factors under IEC standards

Rated voltage factor	Rated time	Application of the VT
1.2	Continuous	VT connected phase-to-phase VT connected between the neutral of a transformer wye and ground
1.2	Continuous	VT connected between phase and ground on an effectively grounded system
1.5	30 s	
1.2	Continuous	VT connected between phase and ground in a system that is not effectively grounded but where tripping in response to ground faults is automatic
1.9	30 s	
1.2	Continuous	VT connected between phase and ground in system where the neutral is either not intentionally grounded or is grounded through a resonant grounding device (i.e., Peterson coil) without automatic ground-fault tripping
1.9	8 h	

Table 15 defines the required power frequency and impulse voltage levels for VTs as a function of system voltage:

Table 15—IEC standard required values of VT insulation

Maximum equipment voltage, U_m, kV rms	Rated power frequency withstand voltage, kV rms	Rated lightning impulse withstand voltage, kV crest
0.72	3	—
1.2	6	—
3.6	10	20 40
7.2	20	40 60
12.0	28	60 75
17.5	38	75 95
24	50	95 125
36	70	145 170

For higher system voltages, refer to Table 4 in IEC 60044-2 (2004).

Where two lightning impulse ratings are shown, the higher rating is recommended for exposed applications.

5.3.2.2 IEC output power ratings for voltage transformers

The rated continuous output (in VA) of VTs under IEC standards is a value selected from the following list:

10 VA, 15 VA, 25 VA, 30 VA, 50 VA, 75 VA, 100 VA, 150 VA, 200 VA, 300 VA, 400 VA, and 500 VA.

5.3.2.3 IEC accuracy ratings of voltage transformers

IEC standards define five accuracy classes for inductive VTs. The required measuring accuracy for each class is given in Table 16.

Table 16—Limits of error for inductive voltage transformers under IEC standards

Accuracy class	Percentage voltage ratio error (±)	Phase displacement (±)	
		Minutes	Centiradians
0.1	0.1	5	0.15
0.2	0.2	10	0.3
0.5	0.5	20	0.6
1.0	1.0	40	1.2
3.0	3.0	Not specified	Not specified

In addition, VTs applied for protective applications are assigned an additional accuracy designation of 3P or 6P. These designates require that the voltage ratio error be no greater than 3% and 6%, respectively, and that the phase displacement be no greater than 120 min (3.5 centiradians) and 240 min (7.0 centiradians), respectively, at both 5% of the VT rated voltage and at the voltage equal to rated primary voltage multiplied by the rated voltage factor (from Table 11).

Capacitive VTs are defined under IEC standards to fall into one of four accuracy classes, 0.2, .0.5, 1.0, and 3.0. The accuracy limits for capacitive VTs are the same as those for inductive VTs with the same accuracy class designation. Capacitive VTs in protective applications also carry a 3P or 6P designation (defined the same as for inductive VTs). However, capacitive VTs are given a transient performance specification under IEC standards.

5.4 Voltage transformer construction

5.4.1 Inductive voltage transformers

Most VTs in low- and medium-voltage applications are inductive, consisting of primary and secondary windings on a ferrous core.

An important physical consideration with VTs is the number of terminals (or bushings). Two terminal (bushing) VTs are primarily intended for use in applications calling for phase-to-phase connection and measurement, but they may also be applied in a phase-to-ground arrangement. Single terminal (bushing) VTs may only be used in phase-to-ground applications.

Conventional inductive VTs are normally the preferred choice for revenue-metering applications because of their predictable accuracy. However, the accuracy of inductive VTs deteriorates at higher frequencies, and therefore inductive VTs are normally not considered ideal for accurately measuring phenomena such as switching transients that include significant high-frequency components.

5.4.2 Capacitive voltage transformers

Capacitive voltage transformers (CVTs) or sometimes referred to as capacitively coupled voltage transformers (CCVTs), are commonly used for protection application in high-voltage applications, 115 kV and above. The primary advantage of CVTs is economic—the cost of a fully-insulated primary winding for use at higher voltages is significant, and CVTs can accomplish the same measurement objectives at appreciably lower cost.

A CVT is nothing more than a capacitive voltage divider. A series-connection of capacitors is applied between phase and ground. The voltage that appears across individual segments of this series connection is proportional to the total phase-to-ground voltage. Typically, CVTs include a small conventional transformer to inductively isolate the secondary from the high-voltage primary.

CVTs are single-terminal devices and are intended for phase-to-ground connections.

While CVTs are routinely used for protection, some users are uncomfortable with the notion of using them for high-accuracy metering applications, especially revenue-metering. CCVTs are, however, preferred for use when it is important that the measurement accurately reflect the full spectrum of frequencies that may exist in the primary system voltage, for example, in quantitatively measuring switching transients.

Historically, CVTs were noted for displaying marked differences in performance under varying ambient temperature conditions. This technical issue has essentially been resolved in modern devices, and type-test procedures address the concern by requiring testing over a range of ambient temperatures.

CVTs also provide the ability to inject signals into the power system. For example, in applications involving power line carrier protection, the high-frequency communications signal is typically injected into the primary power system through a CVT.

5.4.3 Bushing voltage taps

The bushings on high-voltage apparatus, especially power transformers, often include potential taps. These bushings have a pronounced capacitive characteristic, and the voltage that appears at the potential tap is a good replica of the full line-to-neutral bushing voltage.

While useful for specialty testing and diagnostics, bushing potential taps have limited load capability and are rarely used for relaying or ordinary metering.

5.5 Voltage transformer connections

5.5.1 VT polarity

Like CTs, VTs also have polarity, and polarity has precisely the same meaning although different words may be used to define polarity with VTs. With VTs, it is normally said that the voltage at polarity on the secondary is in phase with the voltage at polarity on the primary.

Polarity on VTs is normally identified by marking a primary terminal H1 and a secondary terminal X1. Alternatively, these points may be identified by distinctive color markings.

VT polarity is especially important when the output of a VT is used in conjunction with the output of a CT. Examples of applications where this can be a concern include metering (of both real and reactive power), and directional relaying.

5.5.2 Three-phase wye connection

In high-voltage applications, VTs are almost always applied in the three-phase wye connection. See Figure 13. The major reason for this is that single-bushing VTs (or CVTs) at higher voltages are far less expensive than the two-bushing devices that would be required for the open-delta connection. In addition, the wye-wye connection of VTs produces a faithful replica of primary voltage, with no phase shift from primary to

secondary. Today, this practice is migrating to lower voltage applications where digital technology allows relaying and metering devices to derive phase-to-phase quantities from phase-to-neutral measurements.

Where line-to-neutral loading is expected in medium-voltage systems, VTs are more often connected wye-wye, particularly where metering is required.

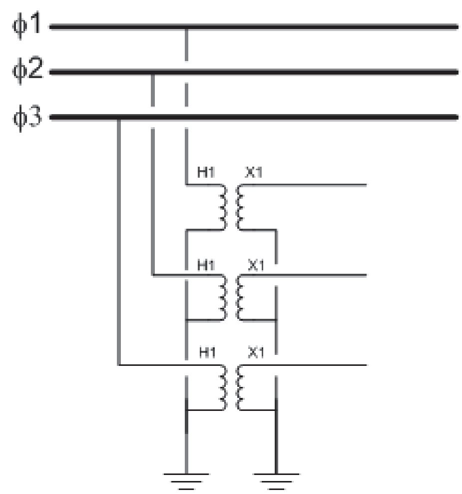

Figure 13—Wye-connected voltage transformers

5.5.3 Open-delta connection

In medium-voltage systems, where system load is balanced between the three phases and, therefore, balanced voltages are anticipated, VTs have traditionally been connected in open-delta. See Figure 14.

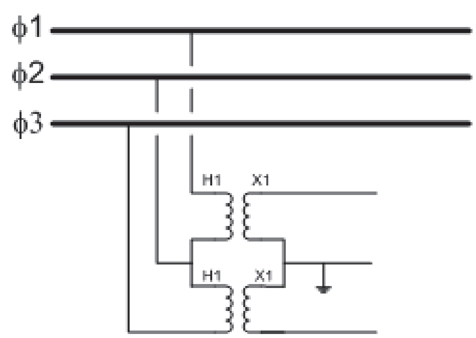

Figure 14—Open-delta voltage transformers

5.5.4 Three-phase broken-delta connection

Occasionally, it is appropriate to use a three-phase wye connection of VTs with the secondaries connected in delta. These applications are sometimes called the broken delta connection because the secondary delta is closed through a voltage relay; since voltage relays tend to have a high internal impedance, this connection behaves as though the secondary delta is open-circuited. The voltage that appears across this secondary delta is proportional to three times the zero sequence voltage present on the primary system ($3V_0$). Therefore, the two primary applications of this connection are:

1. Ground-fault detection on systems where the neutral is intentionally not connected to ground.
2. Zero-sequence polarization of directional ground overcurrent relays.

There are special concerns with the broken-delta connection. Occasionally, broken-delta VTs are used to ground the neutral of an otherwise ungrounded system. When this is done, it is critical to note that the effective impedance inserted between neutral and ground is the relatively high magnetizing inductance of the VTs, and it should be verified that this level of grounding will satisfy system requirements for transient overvoltage control. Also, it may be appropriate to include a loading resistor across the broken-delta secondary to mitigate potential ferroresonance between the VT magnetizing inductance and distributed capacitance on the primary [B5] and [B8].

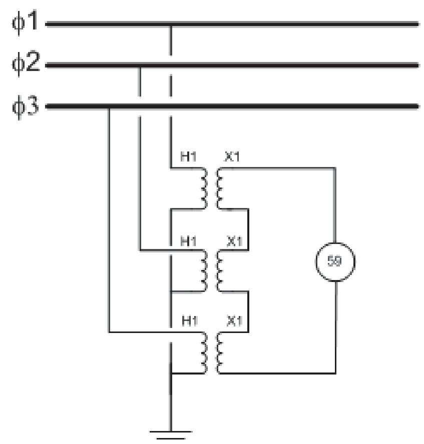

Figure 15 —Broken-delta voltage transformers

5.5.5 Auxiliary VTs

Some protective devices require specific delta or wye voltages. When the VTs are arranged in the three-phase wye connection, auxiliary VTs may be used to introduce either phase shifts, adjust the magnitude of secondary voltage, or derive zero-sequence voltage as required to meet the requirements of those protective schemes.

Auxiliary VTs may also be used in conjunction with primary VTs in the open-delta connection but with some loss of flexibility in achieving desired phase angle displacement.

5.6 Voltage transformer application guide

5.6.1 Voltage transformer fusing

One of the most common application issues associated with VTs has to do with whether the VT should be fused.

It is usually impossible to select primary fuses that actually protect the transformer from overloads or faults in the external secondary circuit. Furthermore, should fuses that have a small enough current rating to actually be of any practical protective value be applied, experience suggests that they would be so fragile that they would represent an undesirable maintenance burden.

That said, some users do use primary fuses, but mainly to isolate failed VTs from the system. That is, primary fuses are used for system protection, not to actually protect the VTs on which they are applied.

Secondary fuses selected to interrupt at loadings below the thermal burden rating may provide some protection for the VT. Where branch circuits are tapped from VT secondaries to supply devices located at a distance from the VT, it may be desirable to fuse the branch at a reduced rating. More importantly, secondary branch fusing may be worthwhile as a means of minimizing the impact of maintenance errors (e.g., where an electrician's screwdriver inadvertently introduces a short-to-ground in the VT circuit).

The use of secondary fuses in pullout fuse blocks also provides a convenient and relatively inexpensive means of introducing a mechanical switch in the secondary VT circuit.

5.6.2 Application of voltage transformers at abnormal frequencies

VTs are designed to be applied on power systems where the operating frequency matches the frequency rating specified by the manufacturer. VT experience increased saturation at reduced frequencies, and other anomalous performance characteristics at frequencies significantly greater than rated. Applications involving measurements at frequencies other than rated frequency are outside the scope of standards and should be reviewed with the respective VT manufacturer.

5.6.3 Use of voltage transformers for station service

IEEE and IEC standards are based on the presumption that VTs are intended to provide voltage signals for measurement and protection. There are, however, instances in which VTs are used to provide auxiliary facilities power, supplying loads such as battery chargers, communications equipment, and lighting. These applications are clearly beyond the purview of applicable instrument transformer standards. The most obvious concern is that the total load applied to the VT should be less than the output rating as specified by the applicable IEEE or IEC standard.

Annex A

(informative)

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